10. A GENERIC RISK ASSESSMENT OF REPRESENTATIVE LAUNCH SCENARIOS

10.1 INTRODUCTION

Since the beginning of US space launch operations in the 1950's, there have been no launch operation accidents that have produced any general public casualties outside any of the Government Launch facilities. There has been some damage to some Range facilities and structures used to support the launches, but little damage to public property outside the perimeter of the launch sites. Considering the fact that there have been unavoidable failures during thirty years of new rocketry and spacecraft testing and streamlining of launch operations, it is evident that the Range Safety Control process and systems in place have prevented and controlled the risk from launch accidents that could have lead to potentially significant claims against the Government.

This proven track record of success for the Range Safety Control systems and practices at the National Ranges may cast doubt on the need to discuss the public risk exposure levels and the potential for third party liability claims. It is worthwhile, however, to discuss the consequences of ELV launch failures in the absence of the Range Safety Control system since proposed commercial space launches could originate at new launch sites (perhaps an island site or an ocean platform); use novel, untested or reconfigured tracking and control systems; and not require an FTS of high reliability on-board ELV's. This approach will permit an assessment of the extent of potential damage and/or casualties that can be avoided by the established Range Control Systems and safety practices (see also Ch.2, Vol.1, and Ch.9). While much of the qualitative hazards analysis of launch-related accidents has been given previously in Ch.5, Vol.2, the intent of this chapter is to provide a coherent, self-contained discussion of generic public risk associated with commercial launch operations for existing ELV's which weighs the consequences of each accident by its probability of occurrence in a Risk Matrix according to the methods and tools illustrated in Chs. 8 and 9.

10.2 RISKS DURING DIFFERENT PHASES OF A TYPICAL MISSION

10.2.1 Pre-Launch Hazards

During the preparation of a vehicle for launch, the chief hazards derive from the storage and handling of propellants and explosives. The Ground Safety procedures applied to stored explosives and propellants that can explode are similar to those used in the transportation and handling of these same materials off-site. The protective measures include quantity-distance requirements, so that parties uninvolved with the launch cannot be affected by any accident. In addition, other structural protection (e.g., hardened concrete) and emergency preparedness measures are used to contain toxic or corrosive materials within the boundaries of the Range in case of an accident on the pad (see also Ch.5, Vol.2).[1,12]

Accidents occurring prior to launch can result in on pad explosions, potential destruction of the vehicle and damage to facilities within range of the blast wave as well as dispersion of debris in the vicinity of the pad. The types of accidents depend upon the nature of the propellants, as discussed in Ch.5. In the case of cryogenic propellants, liquid oxygen alone will cause fires and explosive conditions; if used in association with liquid hydrogen, it can lead to very explosive conditions. Under somewhat ideal conditions, the TNT equivalence of a hydrogen-oxygen propellant explosion can be as much as 60 percent of their weight, while that of an RP-1-oxygen explosion can be 20 percent of the weight of the propellants (see Ch.5, Vol.2).[1]

An accident in handling storable hypergolic propellants could produce a toxic cloud, liable to move as a plume and disperse beyond the boundaries of the facility. The risk to the public will then depend upon the concentration of population in the path of this toxic plume and on the ability to evacuate or protect the population at risk until the cloud is dispersed. It is obviously advantageous if the winds generally blow away from populated areas. There are also specific safety requirements and risks associated with ground support equipment. The design and use of this equipment must incorporate safety considerations.

10.2.2 Launch Hazards

Generally, the on-board destruct system is not activated early in flight (during the first 10 seconds or so) until the failed vehicle clears the Range. This protects Range personnel and facilities from a command explosion. Failures during the very early portion of launch and ascent to orbit can be divided into two categories: propulsion and guidance/control. Lighting, wind and other meteorological hazards (e.g., temperature inversions) must be considered prior to launch countdown.

Propulsion failures produce a loss of thrust and the inability of the vehicle to ascend. Depending on its altitude and speed when thrust ceases, the vehicle can fall back intact or break up under aerodynamic stresses. If the vehicle falls back, the consequences are similar to those of an explosion on the ground. The exception is when intact solid rocket motors impact the ground at a velocity exceeding approximately 300 fps. In that case, the explosive yield may be significantly increased. If there are liquid fuels (hydrogen-oxygen), there is also potential for a large explosion, much higher overpressures and more damage to structures at the launch facility. It could also create higher overpressures off the facility which could break windows and possibly do minor structural damage to residential and commercial buildings (see Ch.5, Vol.2).

Solid rocket motor (SRM) failures can be due to a burn-through of the motor casing or damage or burn-through of the motor nozzle. In a motor burn- through there is a loss of chamber pressure and an opening is created in the side of the case, frequently resulting in structural breakup. The nozzle burn-through may affect both the magnitude and the direction of thrust. There is no way to halt the burning of a solid rocket once initiated. Hence, an SRM failure almost inevitably puts the entire launch vehicle and mission at risk. When there are several strapped-on SRM boosters, as is commonly the case, the probability of a failure of this type is increased, since any one of these failing can lead to mission loss.

The purpose of the Range Safety Control system is to destroy, halt or neutralize the thrust of an errant vehicle before its debris can be dispersed off-Range and become capable of causing damage or loss of life. Without a flight termination system (FTS), the debris could land on a population center and, depending upon the type of debris (inert or burning propellant), cause considerable damage. The destruct system generally is activated either on command or spontaneously (ISDS - the inadvertent separation destruct system is activated automatically in case of a stage separation failure) at or soon after the time of failure. In flight destruction limits vehicle debris dispersion and enables dispersion of propellants, thus reducing the possibility of secondary explosions upon ground impact. The destruct systems on vehicles having cryogenics are designed to minimize the mixing of the propellants, i.e., holes are opened on the opposite ends of the fuel tanks. This contrasts with vehicles with liquid storable propellants (e.g., Aerozine-50 and N_2O_4) where the destruct system is designed to promote the mixing and consumption of the propellant. Solid rocket destruct systems usually consist of linear shaped charges running along the length of the rocket which open up the side of the casing like a clam shell. This causes an abrupt loss of pressure and thrust. It may, however, produce many pieces of debris in the form of burning chunks of propellant and fragments of the motor casing and engines.

The Titan 34D accident on April 18, 1986, about 8 seconds after launch, is an example of a propulsion failure which caused considerable and costly damage to the VAFB facility.[(2)] In this case, the solid rocket case failed and the vehicle fragmented and spread burning propellant over the launch site. Typical debris velocities were 100 to 300 fps. This Titan 34D failure was the result of a burn-through of one of the rocket motor casings. The explosion, which occurred at an 800 ft. altitude, was not a detonation, where there is almost instant burning of propellant accompanied by a significant air blast, but a deflagration, where most of the propellant was not consumed in the explosion, but formed a cloud of flying burning debris. Some of the burning propellant still encased in a section of the rocket motor did appear to explode upon impact. The evidence was a flash of light recorded by a camera, although the camera was not directed at the point of impact. A series of small craters were also observed after the accident. It is believed that some of these craters were formed by violent burning in the soft soil (sand) rather than by explosions. Films do show rebound of propellant chunks and shattering upon the rebound. This type of behavior was also observed in earlier Minuteman failures.

In addition to complete loss of control, there are three other early flight guidance and control failures that have been observed with launch vehicles over the life span of the space program: failure to pitch over, pitching over but flying in the wrong direction (i.e., failure to roll prior to the pitchover maneuver) and having the wrong trajectory programmed into the guidance computer. The likelihood of these circumstances depends upon the type of guidance and control used during the early portion of flight. The types are open or closed loop (i.e., no feedback corrections) and programmer or guidance controlled. In the case of vehicles which use programming and open-loop guidance during the first portion of flight, failure to roll and pitch is possible, although relatively unlikely, based on historical flight data. If the vehicle fails to pitchover, it rises vertically until it is destroyed. As it gains altitude, the destruct debris can spread over an increasingly larger area. Consequently, most Ranges watch for the pitchover and if it does not occur before a specified time, they destroy the vehicle before its debris pattern can pose significant risk to structures and people outside the launch facility or the region anticipated to be a hazard zone, where restrictions on airspace and ship traffic apply. Failure to halt the vehicle within this time can produce a significant risk to those not associated with launch operations.

With open-loop Stage 1 guidance, a launch in the wrong direction can occur due to improper programming or improper roll of the vehicle during its vertical rise. This circumstance, although considered improbable, can be very hazardous. If the Range does not halt the flight immediately, the vehicle could overfly populated regions. Then, even if the vehicle is normal in every other respect, it could drop jettisoned stages on populated areas, creating the potential for damage, injury and loss of life. The detection of improper launch azimuth is usually accomplished visually because radar tracking may not be effective very early in flight. Consequently, in making the decision to halt the flight, the Range must rely on visual observers to relay information about pitchover and azimuth, with possible time-delays.

With vehicles which are inertially guided from liftoff, failure in pitchover or roll is unlikely. It is possible, but extremely unlikely, that an inertially guided vehicle could have the wrong set of guidance constants, i.e., the wrong trajectory, stored in its guidance computer. To the observer this will appear the same as an improper roll (flight azimuth).

If a solid rocket loses thrust or has a change of direction of the thrust vector, the vehicle control system will try to compensate with the remaining engines. The result will be an aberrant corkscrewing behavior until the control system is totally overwhelmed, and then a tumble. With atmospheric forces present, the stages should break apart by this time.

Generally, rapid hard-over tumbles of failing vehicles do not cause the vehicle to move significantly cross-range off the intended path of flight. It is the gradual turn that is of greater concern to the Range Safety Officer. If the vehicle turns slowly, it can move a significant distance cross-Range. This type of failure is rare and difficult to rationalize with most flight-tested ELV systems, but the unexpected must be anticipated. An example of the unexpected is the behavior of the solid rockets from the Space Shuttle after the failure of the Challenger.[3] They were supposed to tumble and not offer much of a dispersal hazard. Instead they turned very little and had to be destroyed before they could become a threat to a populated area.

Of greatest concern to Range Safety Control during the steep ascent phase, is the capability of the vehicle to wander off-course immediately following a malfunction. The Range Safety Control system must be able to respond before debris becomes a hazard. Consequently the design of the destruct lines must take into consideration: (1) the delay between decision and destruct; (2) the highest rate that the vehicle can move its IIP toward a protected area; (3) the effect of the winds; and (4) the contribution of any explosion to the scatter of debris.
During the early boost phase the vehicle experiences its greatest aerodynamic loads and heating. As the vehicle accelerates, the dynamic pressure ($1/2\ pv^2$) increases until the decrease in density (p) due to higher altitude overcomes the effect of increasing velocity (v). During the period of high airloads the vehicle is more vulnerable structurally and likely to break apart if it has a high angle of attack or begins to turn abruptly. The Space Shuttle, for example, with its complex configuration and lifting surfaces, is so sensitive during this period that the liquid propelled main engines are throttled down to keep the

dynamic pressure within specified limits. One of the major fears during this phase is an abrupt change in wind velocity during ascent (a wind shear). This causes a rapid change in angle of attack and requires rapid and appropriate response by the control system.

The potential for damage to ground sites from a launch vehicle generally decreases with time into flight since fuel is consumed as the vehicle gains altitude (see Fig.5-6 in Ch.5, Vol.2). If it breaks up or is destroyed at a higher altitude, the liquid fuels are more likely to be dispersed and lead to lower concentrations on the ground. In addition, if there are solid propellants, they will have been partially consumed during the flight period prior to the failure and will continue to burn in free fall after the breakup.

Meteorological conditions contribute to the potential for off-site damage. Temperature inversions and wind shears can cause shock waves, which normally turn upward, to turn down and possibly focus at locations distant from the launch site.[4] This results in significantly higher overpressures locally, than the overpressures from shockwaves moving in a normal adiabatic atmosphere (an atmosphere where the temperature decreases with increasing altitude). Another meteorological influence is the wind, which can deflect falling debris towards populated areas.

Very early in flight, when the vehicle is still close to the ground, there is less opportunity for debris to be scattered. The debris fall within a footprint which is affected by the range of ballistic coefficients of the pieces, the wind speed and direction, velocity contributions due to explosion and random lift (see also Ch.2, Vol.1 and Ch.7, Vol. 2). To understand the make-up of the debris footprint, first observe the "centerline" as shown in Figure 10-1.[5] This centerline represents the spread of debris impact and drag effects when there is no uncertainty due to wind, lift, etc.

Debris which are very dense and have a high ballistic coefficient (β) are not as affected by drag and will tend to land closer to the vacuum IIP. High ballistic coefficients can be associated with pumps, other compact metal equipment, etc. Panels or pieces of motor and rocket skin offer a high drag relative to their mass (a low ballistic coefficient) and consequently slow down much more rapidly in the atmosphere. After slowing down they tend to fall and drift with the wind. This effect is also shown in the figure. A piece of debris with a very low ballistic coefficient (β=1) is shown to stop its forward flight almost immediately and drift to impact in the direction of the wind. Pieces having intermediate value ballistic coefficients show a combination of effects and fall along a centerline. From a lethality standpoint, the pieces having a higher ballistic coefficient impact at a higher velocity and can cause more damage (depending

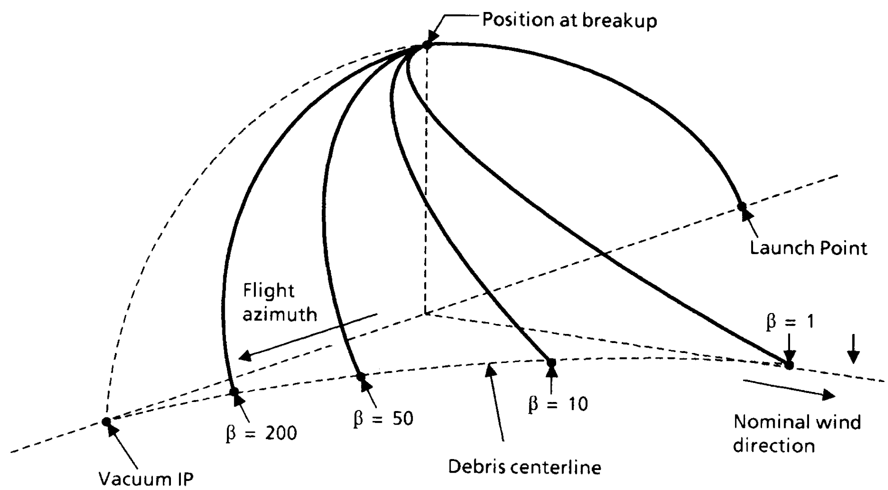


FIGURE 10-1. BEHAVIOR OF DEBRIS AFTER VEHICLE BREAK UP

upon their size). The debris will not necessarily impact along the centerline. The velocity impulses at breakup, the wind and tumbling behavior all contribute to uncertainties about the impact point. This is illustrated in Figure 10-2.

When all of the factors affecting debris transport and dispersal to impact are considered at once, the effect is a pattern as shown in Figure 10-3. The boundaries of the debris dispersion footprint are not precise but rather represent a contour which contains, say, 95 percent of the debris. Thus, when considering the hazard to structures or people on the ground, one must consider the hazard area for debris impacts in the terms of a pattern which is dynamic. It grows rapidly as the vehicle gains altitude, as illustrated in Figure 10-4 for a vehicle launched from Vandenberg Air Force Base. Note the geography and the fact that part of the debris pattern dwells over land for a significant period of time. The time interval that the debris impact pattern dwells over land depends upon the direction and strength of the wind.

If the wind, as in this case, is blowing very hard from the southwest, the low ballistic coefficient portion of the pattern will tend to stay over the land. If the wind is blowing from the northeast, the pattern will move very rapidly out to sea. This

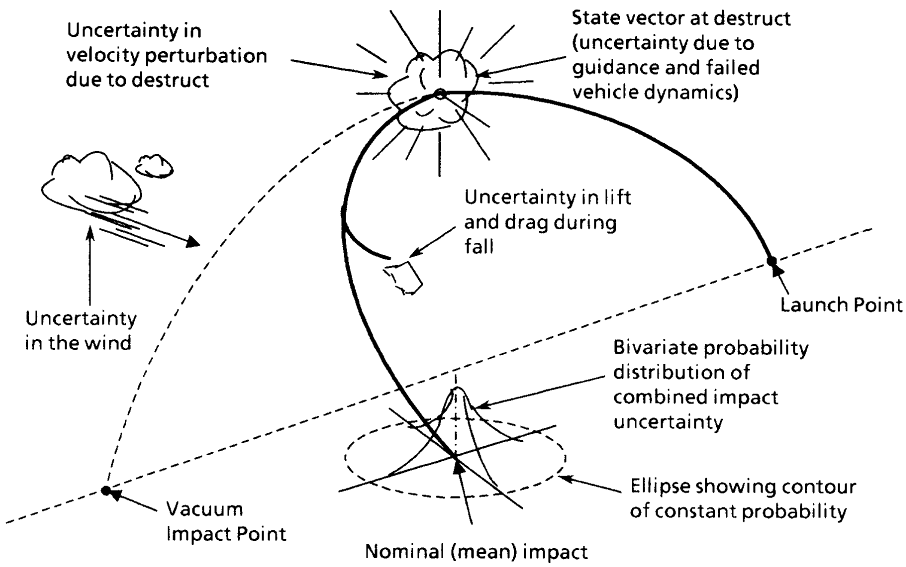


FIGURE 10-2. DEBRIS IMPACT DISPERSION

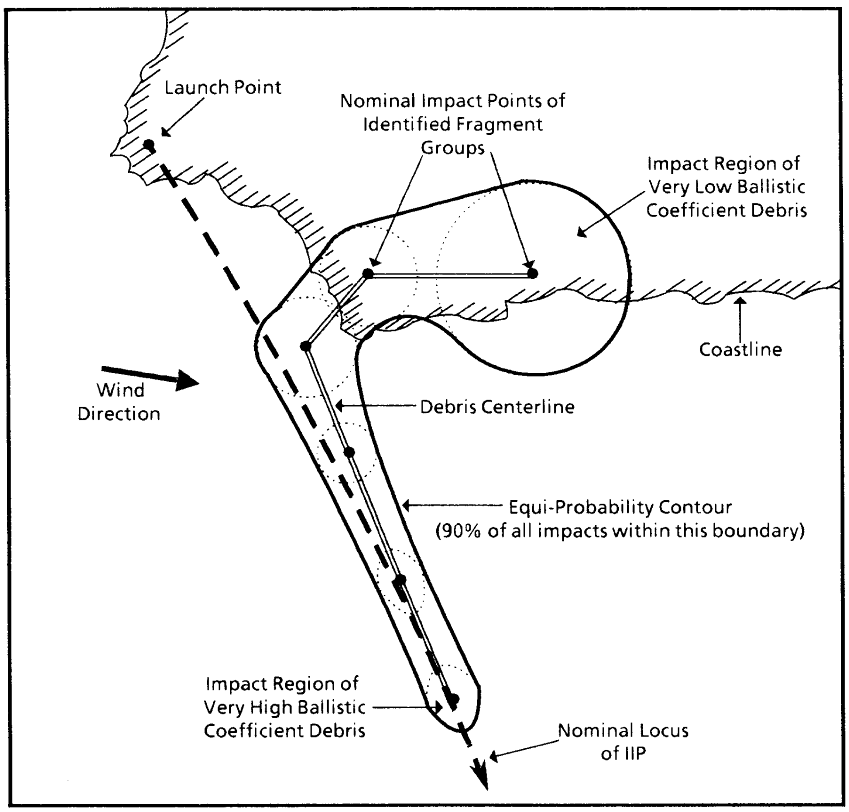


FIGURE 10-3. A TYPICAL DEBRIS DISPERSION AT IMPACT PATTERN

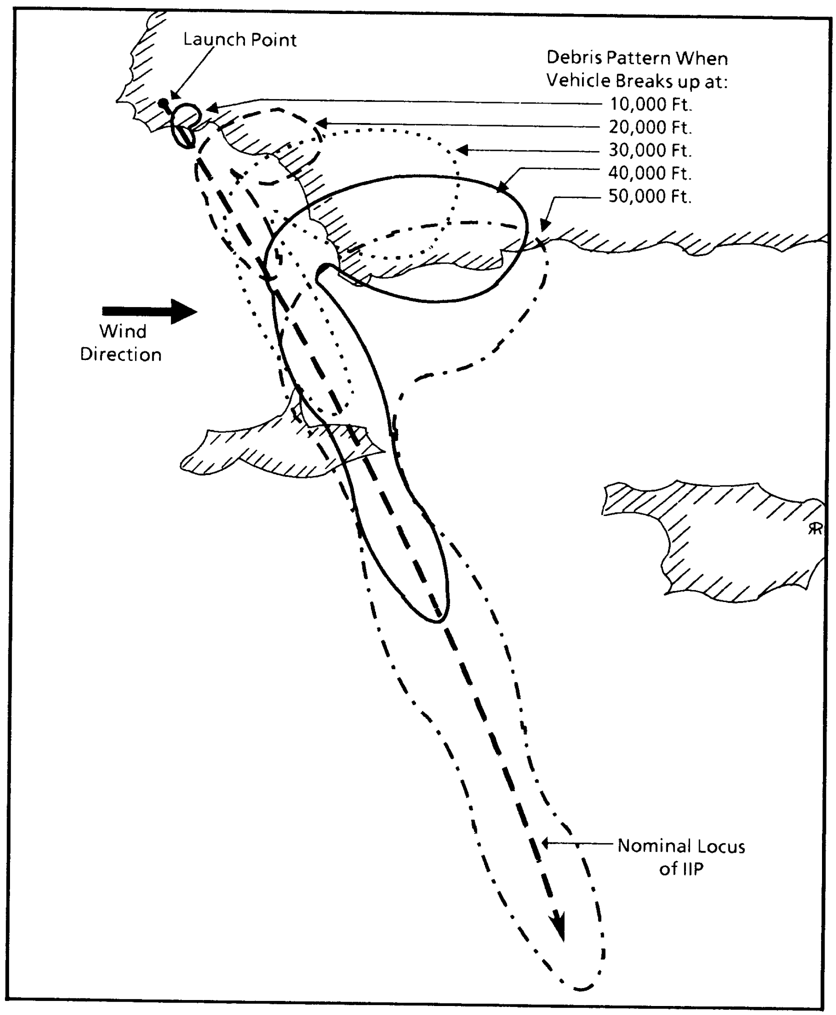


FIGURE 10-4. GROWTH OF THE DESTRUCT DEBRIS IMPACT DISPERSION PATTERN

demonstrates the very important role of wind in evaluating risks of a launch. Depending on prevailing meteorological conditions, including clouds, visibility, atmospheric electricity, temperature and wind conditions, a launch may be postponed until adverse conditions subside. The bulge in the center of the growing debris pattern in Figure 10-4 is due to debris which have velocities imparted to them from an explosion (spontaneous or destruct action). The upper-right-hand portion of the debris pattern consists of debris which have a high drag to weight ratio, slow down quickly and are carried by the wind, which, in this case, is blowing from the west. Notice how the debris pattern stretches as the vehicle increases in altitude. This effect continues until the vehicle reaches an altitude where aerodynamic drag no longer has an effect on dispersion.

For all launches, the boosters, sustainers and other expendable equipment are always jettisoned and fall back to the Earth. Therefore, in planning a mission, care must be taken to keep these objects from impacting on land, offshore oil platforms, aircraft and shipping lanes. The impact locations are normally quite predictable, so risks can be avoided or minimized.

As mentioned earlier, during the entire history of the space and missile programs at VAFB and Cape Canaveral/Cape Kennedy, no errant launch vehicle has ever been allowed to wander over a populated area near the launch site and deposit debris upon it. As a consequence there have been no claims, damages or casualties. This is a convincing argument in the support of continued safe launch and mission planning and approval procedures, reinforced by a reliable Range Safety Control system.

10.2.3 Pre-Orbital Hazards

After jettison of the booster stage and, in some cases, the solid rockets, the remaining core vehicle usually contains only liquid propellants and is at a fairly high altitude. If a failure occurs and no destruct action takes place, the vehicle may fall and remain largely intact till ground impact. Depending upon the initial altitude, the airloads during the fall may become sufficient to contribute to the vehicle breakup. If this occurs, the propellants will most likely be dispersed and the only hazard will be from impacting "inert" debris. In the unlikely event that the tanks do remain intact, some explosion may occur at impact. If the propellants are hypergolic, as in the case of the Titan, there may be considerable burning and a cloud appearing in the impact area. In this latter case, the damage from debris impact will probably be less than the hazard from the toxic propellants. When an altitude is reached where the vehicle stages can no longer remain intact because of airloads and heating, the only hazard will be due to impacting debris.

If a destruct or thrust termination system is used to halt ascent, as is usually the case, the propellants will be dispersed and should offer very little threat to people on the ground. A product of the destruct action will be inert debris, which could present a hazard at ground impact (for fire, explosion and toxic hazards, see Ch.5, Vol 2).

During the boost trajectory of almost any space vehicle from any US National Range, the IIP will at some time pass over occupied land. For Titan 3 launches due east from Cape Canaveral, the IIP will begin to pass over Africa at t = 475 seconds, and leave Africa 3 seconds later. For some southerly launches from Vandenberg Air Force Base, the IIP can pass over southern Argentina and Chile. Activation of the destruct system is of no value at this point because it poses risks of land impact. It is often better to let the failing vehicle continue with the hope that it will clear the land area and impact in the ocean. The threat from either launch condition is relatively small because in both cases the IIP is traveling very fast over land areas (hundreds of miles per second). If, for example, the failure rate of the Titan 3 were uniformly 0.000075 failures per second (historical launch failure probability of .036 divided by 480 sec. of burn operation) and the time required for the IIP to cross Africa is 3.2 seconds (see Figure 10-5), then the probability of failing and causing debris to fall on Africa is 3.2 times 7.5×10^{-5} or 2.4×10^{-4} (one chance in approx. 4200). If the combined cross section of debris which survive to land impact is on the order of 1000 sq. ft.,and the average density of population which can be harmed by the debris is 50 per square statute mile (according to Ref. 5, this figure is higher than the average of the population densities of Zambia, Angola and Zimbabwe), then the average number of casualties per launch due to an African impact is:

$$E_c = \text{(failure rate)x(dwell time over land)x(debris "casualty area")x(population density)}$$

$$= 7.5 \times 10^{-5} \times 3.2 \times 1000 \times (50/5280^2) = 4 \times 10^{-7}$$

This corresponds to less than one chance in a million of a casualty per launch. Whereas Range Safety Control systems can act very positively to restrict and prevent debris from falling on populated areas earlier in flight, there is no effective risk control when the flight plan calls for a direct land overflight, such as the one discussed above. Consequently the casualty expectation of 8×10^{-7} is the same with or without a flight termination system on-board the ELV.

The potential for damage from the impact is based on the area of falling debris (in this case estimated to be 1000 ft.^{2}) and the likelihood of impacting a structure of value. With a population

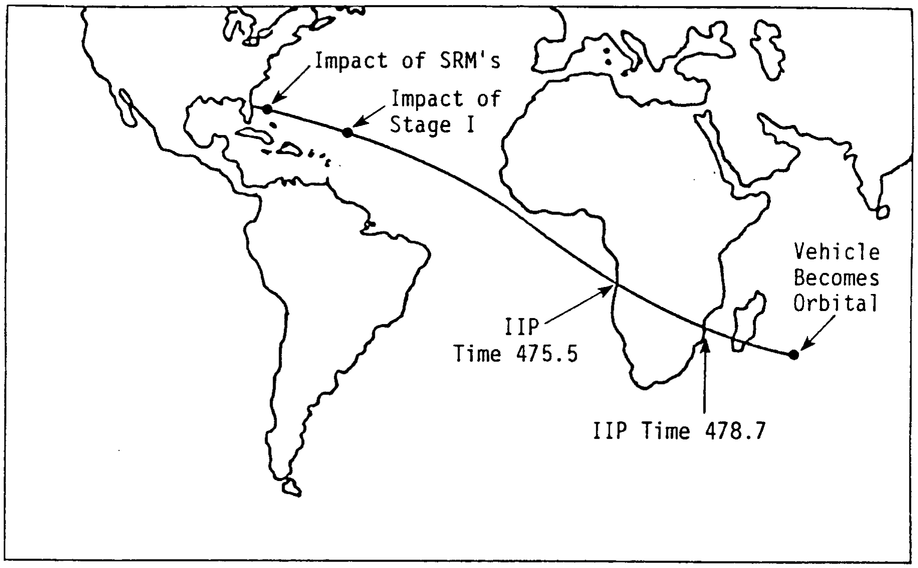


FIGURE 10-5. LOCUS OF IIP FOR A TYPICAL TITAN III LAUNCH FROM CAPE CANAVERAL (ETR)

density of less than 50 per square mile, the density of such structures is rather low. As an example, assume the surviving debris consist of four pieces, each having a cross-section of 250 $ft.^2$, and the average structure is 600 $ft.^2$ with, on the average, one person per structure. (This is an attempt to account for both residential and commercial structures very conservatively.) A structure will be hit if any edge is hit by the debris. This is pictured in Figure 10-6.

The effective area of impact is therefore a combination of the structure area and the debris cross-sectional area. In this case the effective impact area becomes approximately 3400 $ft.^2$. The probability of any impact on a structure becomes:

P_i =(failure rate)x(dwell time)x(effective impact area)x(structural density)x(no. of fragments)

$= 7.5 \times 10^{-5} \times 3.2 \times 3400 \times (50/5280^2) \times 4 = 5.5 \times 10^{-6}$.

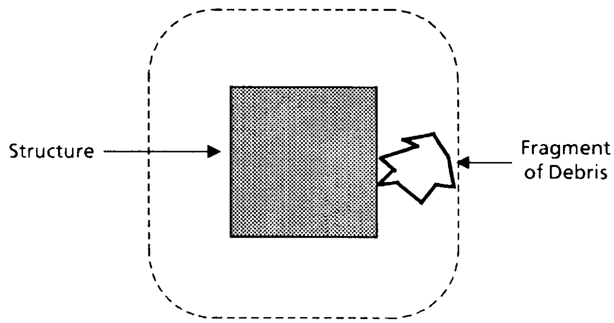


FIGURE 10-6. MODEL CALCULATION OF THE EFFECTIVE AREA OF IMPACT

Thus, in this example the probability of hitting and damaging a structure is approximately 1 in 100,000. If a monetary value or range thereof, were assigned to the structures at risk, then the expected loss could be tied to both the severity and extent of damage (the consequence) and to the very low probability of its occurrence.

A similar analysis can be performed for launches from Vandenberg Air Force Base (see Figure 10-7) when the IIP passes over the southern portion of South America.

According to Ref. 7 and to Figures 10-8 and 10-9, an ELV would have to violate current azimuth restrictions in order to overfly South America (although some flights may overfly Antarctica or Australia at much greater altitudes). The dwell or transit time over Chile and Argentina will be no more than 1.4 seconds. If all other parameters of the casualty expectation and impact probability equations are assumed to be the same, then the E_c and the P_i will be less than those over Africa by the ratio of 1.4/3.2.

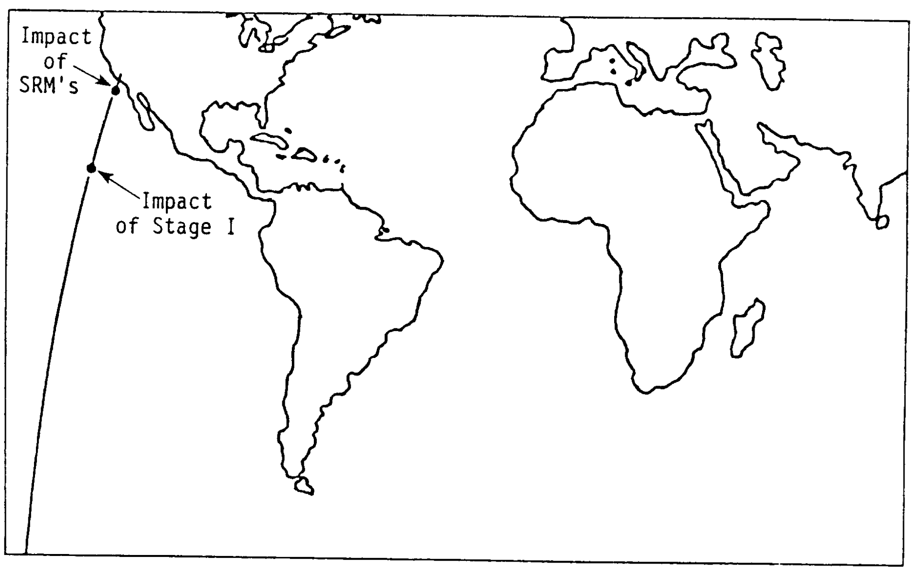


FIGURE 10-7. LOCUS OF IIP FOR A TYPICAL TITAN III LAUNCH FROM VANDENBERG AIR FORCE BASE (WTR)

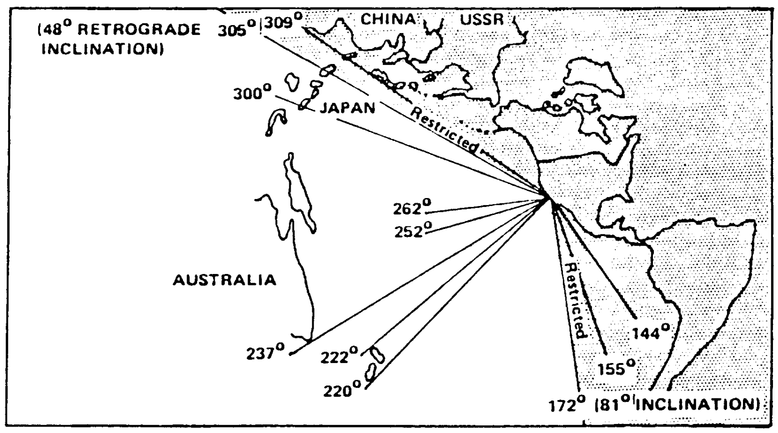


FIGURE 10-8. WTR GEOGRAPHIC LAUNCH AZIMUTH CONSTRAINTS (REF. 7)

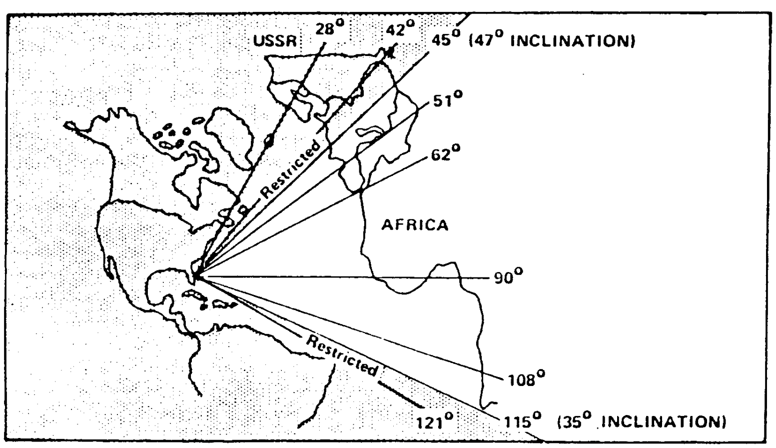


FIGURE 10-9. ETR GEOGRAPHIC LAUNCH AZIMUTH CONSTRAINTS (REF. 7)

Thus, very approximately, the casualty expectation for overflight over the southern region of South America will be 1.75×10^{-7} and the impact probability on a dwelling or commercial structure will be 2.3×10^{-6}.

On-orbit collision hazards, once the satellite has been properly inserted into final orbit, have been discussed in detail in Ch. 7. Similarly, orbital decay and re-entry hazards for satellites and spent rocket stages have been addressed in Ch. 8. Although they contribute to the overall space mission- related hazards, they will not be discussed any further here.

10.3 LAUNCH SITE RISK CONSTRAINTS

The location of the launch facility has a significant impact on the options for launch missions. Launches to the east always benefit from the west to east rotation of the Earth. Consequently, equatorial orbits (0^o inclination) are best achieved by launching from facilities which are near the equator and have a broad ocean area to the east of the launch site. Figures 10-8 and 10-9 above, show the acceptable and restricted azimuths for launches from the USAF Eastern and Western Test Ranges.[(6)] It becomes apparent that ETR is best suited for launches into equatorial orbits and WTR is best suited for achieving polar orbits.

Launches at ETR can also have inclinations other than 0^o. If a vehicle is launched at an azimuth of 45^o from true north, an orbit with an inclination angle of approximately 47^o will result. A satellite in an orbit inclined at 47^o would cover a groundtrack over the region of the Earth between $\pm 47^o$ latitude. From a risk standpoint, as the launch azimuth decreases, the locus of IIP moves closer to the East coast of the US. and Canada. There is also considerably more overflight of countries in the Eastern Hemisphere, with potential political and international repercussions for a space launch accident.

The lowest risk to populated areas is almost always associated with missions where the launch azimuth is perpendicular to the coastline and the wind blows in the direction of the launch. This situation is experienced with many launches at the Eastern Test Range (from Cape Kennedy or Cape Canaveral). Launches into polar orbit from Vandenberg Air Force Base have a southerly launch azimuth, which is perpendicular to the coast at the launch site, but then moves parallel to the coast as the California coastline becomes more aligned north to south. Prevailing winds in the region of the Vandenberg launch site tend to be more onshore and this must be accounted for in establishing destruct lines for Range Safety Control.

10.4 VARIATION OF RISK DUE TO MISSION PROFILE, LAUNCH VEHICLE AND PAYLOAD

10.4.1 Relative Risks of Missions

Missions can be broadly categorized in terms of their orbital parameters: inclination, eccentricity, perigee and apogee altitude. The risks associated with different final orbit inclinations are those associated with the initial launch azimuth necessary to support the sequence of boost and transfer operations needed to achieve the desired final orbit inclination. The risks associated with launch azimuth and site constraints are discussed in Section 10.3. Satellites will re-enter within a few years due to orbital decay from Low Earth Orbits (LEO), but will not from geosynchronous orbits (GEO) (See Ch. 8). Thus geosynchronous orbits offer considerably less risk from the re-entry hazard. The ELV launching a satellite into a geosynchronous orbit must carry more propellant in the initial orbiting vehicle and more stages. The additional propellant in the upper stage (up to a factor of 3) may increase the hazard by a proportionate fraction (percent) for launch accidents on or near the ground. Moreover, insertion of a payload into GEO involves more orbital maneuvers, more stages and a greater fuel load, hence greater overall risk of failing hardware and mission failure. For example, payload delivery to GEO orbit, as shown in Figure 10-12, involves firing an apogee kick motor (AKM) and a perigee kick motor (PKM).

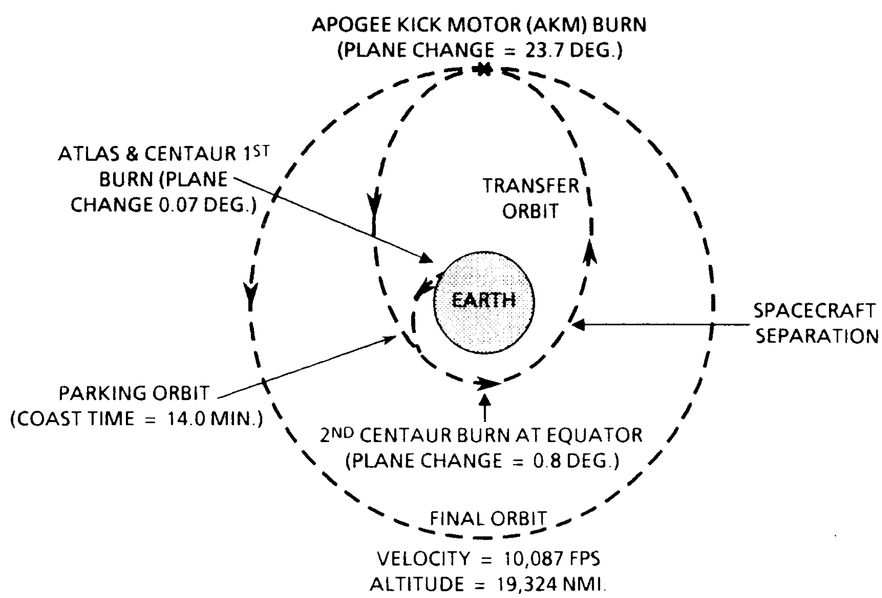


FIGURE 10-12. SEQUENCE OF EVENTS FOR THE ATLAS/CENTAUR ON A GEOSYNCHRONOUS MISSION

However, even if the mission fails to insert the payload into the correct final orbit, public hazards may not increase unless a highly elliptical transfer orbit leads to early uncontrolled re-entry of upper stages and payload or an on-orbit explosion creates collision hazards for GEO and LEO operational satellites.

However, for accidents at high altitude when the vehicle is near orbital, the vehicle with a geosynchronous orbit destination will have less inert debris and the propellant will probably be consumed before ground impact. Hence, in this case, the Low Earth Orbit vehicle will have a larger casualty area and offer a somewhat greater overall risk. In general, the changes in risk level due to the mission profile are relatively small, with the exception of missions requiring restricted azimuths or riskier staging and orbital maneuvers for achieving the mission objective.

10.4.2 Hazardous Characteristics of Typical ELV's

Two ELV's, Atlas/Centaur and Titan III, are the primary subjects of this discussion, although the Delta is also discussed briefly. They offer a broad range of payload lift capacity, they are the largest of the currently available vehicles and they present a variety of propulsion types and representative associated hazards. Furthermore, a hazard analysis for two plausible accident scenarios, based on a typical Delta vehicle and flight profile as a function of time after launch and down-range and altitude evolution, was presented earlier in Figs. 5-5, 5-6 of Ch.5, Vol.2.

10.4.2.1 Titan - The basic Titan III is illustrated in Ch. 5, Figure 5-4. Its central core vehicle consists of two liquid fuel stages, a Transtage and a payload. Two solid rockets (zero stage) are attached to the first core stage and these fire at liftoff and continue until their fuel is consumed. The first core stage is ignited near the end of the solid rocket burn (about 108 seconds after lift-off). After the solid rocket fuel is depleted and the first stage ignites, the empty solid motors are jettisoned (approximately 116 seconds after liftoff). The first stage continues to burn until approximately 273 seconds after liftoff, when its fuel is depleted and the stage is jettisoned. The fairing around the payload is also jettisoned at this time to reduce the weight that will have to be accelerated by the core second stage engine. The fairing is used to reduce the drag and protect the payload during ascent in the atmosphere. At the time of jettison, the vehicle is at an altitude of 400,000 feet (130 km) and is essentially out of the atmosphere. The second core stage fires up immediately and thrusts for 216 seconds. The Transtage has a restartable rocket motor used for orbital maneuvers. Various upper stages can be added for mission and payload flexibility.

During a normal mission, the only risks offered by the Titan are from vehicle hardware which is jettisoned. The impact locations and the approximate locus of IIP for launches from Cape Canaveral are shown in the map in Figure 10-5. The Stage 1 engine covers are not shown there, but are dropped off during the zero-stage solid rocket motor phase of flight. This particular launch trajectory is intended to have a minimum inclination angle in order to support transfer to a geosynchronous orbit.

The impact locations and the approximate locus of IIP for a Titan launch from Vandenberg Air Force Base are shown in the map in Figure 10-7. The requirements for "polar" orbits may not actually need fly over of the poles, but rather very high inclination angles, such as 70^{o}. In addition, launches with inclination angles lower than 90^{o} from VAFB can have larger payloads. Consequently, launches from VAFB may have a range of launch azimuths, as indicated in Figure 10-7, depending on the minimum orbital plane inclination angle.

The liquid fuels which propel the core vehicle and Transtage of the Titan are non-cryogenic and storable: Aerozine-50 and nitrogen tetroxide used in the core vehicle are highly toxic, if released by accidental venting or a spill (see Appendix B and Ch.5, Vol.2). Pre-launch and launch hazards are controlled by handling and storage regulations and by specifying optimal weather conditions for launch which permit toxic vapors and plume dispersal in case of an accident. If the vehicle is destroyed, these hypergolic propellants do not react as energetically as cryogenic propellants. The spontaneous ignition does not allow them to mix before igniting and, consequently, they burn, but have no significant explosion. However, there was an exception: On March 16, 1982, a Titan II, which is basically the first two core stages of the Titan 3, blew up in its silo at Little Rock Air Force Base near Damascus, Arkansas. A very significant explosion resulted which destroyed the entire facility. The magnitude of the explosion was ascribed to the confinement provided by the silo, which did not permit the propellants to scatter while burning. On the other hand, tests of the destruct system of the Titan have generally indicated that the unconfined burning propellants have very little explosive energy.

The more pressing problem with Titan liquid propellants is their toxicity and corrosivity. The destruction of the vehicle may produce a white and reddish-brown (Aerozine-50 and N_2O_4) cloud which is very toxic and also very harmful to vegetation.

In addition to the liquid propellants, the Titan has strap-on solid propellant motors (similar to the Space Shuttle). The emissions from these engines also contain contaminants which, in high concentrations, can be detrimental to agriculture. The main hazard associated with the solid rockets is their explosiveness, the resulting overpressure and the spread of burning debris. Unlike liquid rockets, solid rockets, once ignited, cannot be shut down without being destroyed. Destruct action will always produce a conflagration and dispersion of burning debris. An impact test of an intact Titan solid rocket booster in 1967 indicated that the resulting explosion would be equivalent to TNT having a weight of 7.5 percent of the weight of the propellant in the rocket.[7] Some individuals in the explosive safety field believe, that under the right circumstances, this equivalent yield could be doubled. Others have the opinion that, without impact at a significant velocity, the stage will have no TNT equivalence (see also Ch.5, Vol.2, for a discussion of yield uncertainties).

10.4.2.2 Atlas/Centaur - The Atlas/Centaur is illustrated in Figure 5-7. It is basically a two-stage vehicle consisting of an Atlas first stage and a Centaur upper stage. The Atlas is a liquid oxygen (cryogenic) and RP-1 (hydrocarbon) powered vehicle while the Centaur upper stage is powered by liquid oxygen and liquid hydrogen. Neither vehicle offers a toxic threat, but both are volatile, particularly the hydrogen/oxygen Centaur stage. The primary hazards are blast overpressure and debris from a potential explosion.

At lift-off, the Atlas has thrust provided by three rocket engines. After 155 seconds of flight, the two outer engines (called the boosters) are shut down and jettisoned on rails (3 seconds later). The remaining sustainer engine, which is designed to be more efficient at higher altitudes, continues until all of the fuel has been consumed. During sustainer operation, equipment which served a purpose during the operation within the atmosphere is also jettisoned. Once the sustainer engine is shut down, the Atlas stage is jettisoned, the Centaur engines are ignited and the flight continues. The Centaur has two burn periods, the first to place the Centaur and payload into orbit and the second to put the Centaur and payload into a transfer orbit. The Centaur is separated from the payload while in the transfer orbit. A solid propellant rocket (Apogee Kick Motor or AKM) on the payload may provide the final thrust to place the payload in the geosynchronous orbit; other payloads may use a liquid fueled motor for final GEO emplacement.

The same two missions which were discussed for the Titan are considered, one producing a low polar orbit and the other producing a high equatorial orbit (geosynchronous). The Atlas/Centaur is a smaller vehicle than Titan and can place about 40 percent of the Titan payload in a geosynchronous orbit. Figures 10-10 and 10-11 show the IIP loci for Atlas/Centaur

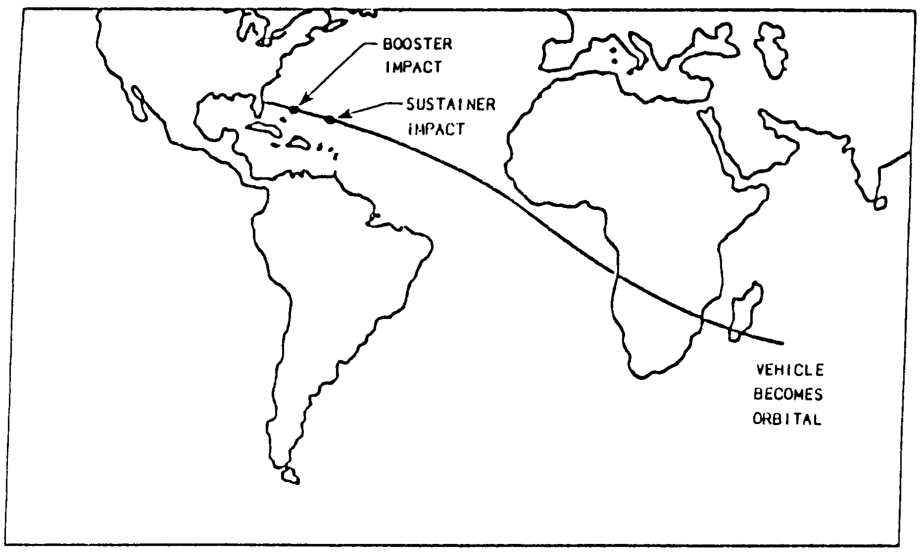


FIGURE 10-10. LOCUS OF IIP FOR A TYPICAL ATLAS/CENTAUR LANCH FROM CAPE CANAVERAL (ESMC)

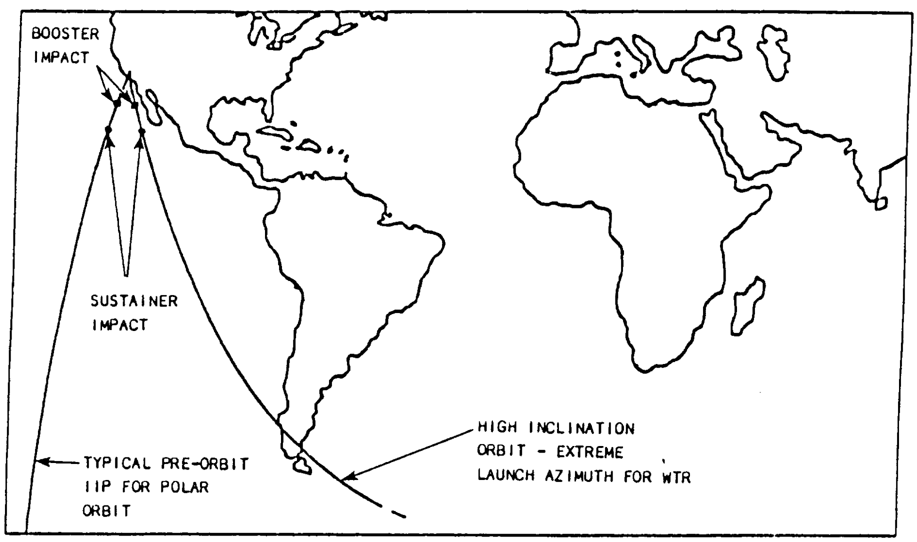


FIGURE 10-11. LOCUS OF IIP FOR A TYPICAL ATLAS/CENTAUR LAUNCH FROM VANDENBERG AIR FORCE BASE (WSMC)

missions from ESMC and WSMC during the pre-orbital phase. During a normal mission, the only hazards associated with the Atlas/Centaur launch are from the jettisoned spent stages, whose impact locations are shown in the figures.

The sequence of orbital events for an Atlas/Centaur FLTSATCOM mission is shown above in Figure 10-12.[3] This is a mission very similar to any other Atlas/Centaur geosynchronous mission, although in this particular case, there is no initial parking orbit. The vehicle, after becoming orbital, continues to accelerate directly into the transfer orbit. Note from Figure 10-12 that the Apogee Kick Motor burn also provides the plane change necessary to achieve an equatorial geosynchronous final orbit.

The hazard potential for the Atlas/Centaur launch will decrease with time into mission as the vehicle and payload gain altitude and propellant is consumed (see Figs. 5-5 and 5-6 in Ch.5, illustrating the risk vs. time for a Delta vehicle). The RP-1 propellant will not be absorbed into the atmosphere, but it will become more widely dispersed as the vehicle reaches a higher altitude. Note that RP-1 fuel is not toxic or corrosive in the same sense as hypergolic liquid propellants.

Fewer pieces of debris are expected from an Atlas/Centaur destruct than for a Titan. This is because of its smaller size and it uses only liquid rocket engines. However, the structure of the Atlas is more fragile than that of the Titan and will most likely break into more pieces than the Titan core vehicle. The very thin Atlas skin pieces will probably scatter more in the wind than the Titan pieces and, consequently, the low ballistic coefficient portion of the Atlas debris pattern will show greater dispersion. In this case, greater dispersion does not mean greater risk to ground objects since Atlas debris are lighter and smaller.

If a failure occurs during the Centaur sustainer burn phase of the flight and no destruct action takes place, the vehicle may remain somewhat intact, depending upon its altitude at that time and on the nature of the failure. Normally, the airloads during the fall will cause vehicle breakup. If this occurs, the propellants will be dispersed and the only hazard will be from impacting "inert" debris. If the tanks were to remain intact, some explosion might occur at ground impacts. However, it is very unlikely that the tanks will remain intact under high airloads given their structural vulnerability.

The principal hazard anticipated is damage from impacting debris. If the vehicle is destroyed by a destruct command, there will be more numerous pieces of debris, but the vehicle will not have been allowed to wander over a possibly populated area.

For launches of geosynchronous satellites from Cape Canaveral, the IIP will move over Africa late in pre-orbital flight, as described for the Titan in Section 10.2.3. The previous discussion of debris impact hazards to Africa and South America is also applicable to Atlas/Centaur, except that it will have less massive debris and the risks may be reduced by as much as a factor of two.

10.4.2.3 Delta - The Delta launch vehicle offers the variety of propellants and components of both the Titan and the Atlas/Centaur vehicles. The Delta has strap-on solid propellant boosters (Castor 4 for Stage 0), a core booster stage (Stage 1) which uses cryogenic liquid oxygen and RP-1, an upper stage (Stage 2) which uses liquid storable propellants (Aerozine-50 and N_2O_4) and a Stage 3 which has a solid rocket motor. The Delta has been launched in a variety of configurations with different numbers of solid rocket boosters and different upper stages. For example, the enhanced Delta configuration, illustrated in Ch.4, Vol.1, has the capability to place 5,500 lbs. of payload into a Low Earth Orbit and 2,800 lbs. of payload in a Geosynchronous Transfer Orbit. The hazards from a typical Delta launch failure have been discussed qualitatively and illustrated quantitatively in Ch.5, Vol.2.

From a comparative risk standpoint, most of the elements of the Delta are on a smaller scale, but there are more of them: there is considerably less hypergolic propellant than on the Titan (see Ch.4 and App. B); there are solid boosters as on the Titan, but they are much smaller and more numerous; there is also less cryogenic propellant in the vehicle than the Atlas/Centaur and there is no explosive and combustible liquid hydrogen fuel. A strap-down inertial guidance system provides guidance throughout booster and upper stage flight. The Delta was considered the most reliable ELV by NASA with an overall failure rate of 6.7 percent, due to 12 failures out of 181 launches; only four launch failures required destruct action. Only six failures led to re-entry of various stages and payload and only one of the six led to ground impact, but no damage was reported (see Table 3-5, Cap. 3, Vol. 1). A discussion of ELV reliability and the implications for public safety from the historical launch statistics were also discussed in Ch.3, Vol.1) The most recent launch accident (Delta 178, on May 3, 1986, at Cape Canaveral) occurred 71 seconds after launch when the main engine was prematurely shut-off by an electrical short, the vehicle tumbled out of control and had to be destroyed by Range Safety (see Ref.to Mishap Report, Ch.9). The NOAA weather satellite GOES-G payload was destroyed; no damage or injury resulted from debris.

10.4.3 Payload Contributions to Launch and Mission Risk

The payload can contribute to overall launch and mission hazards in several ways:

(1) The payload can initiate a malfunction in the launch vehicle by causing a failure (e.g., electrical short or surge) or an explosion during launch which could affect the rest of the vehicle. Generally, the payload is unlikely to cause a launch vehicle failure.

(2) The payload could contribute to the amount of the hazardous material resulting from the accident. Normally this would be in the form of propellant, but if a nuclear heat source is considered, the debris from an accident could present a significant radioactive hazard (see Chs. 7 and 8).

(3) The payload could re-enter and impact on land along with other destruct debris, in case of a launch failure that requires destruct action.

Any payload-related hazards to the public will have to be identified, examined, quantified and managed to tolerable levels as part of the DOT/ OCST licensing safety audit (see Ch.1, Vol.1).

10.5 BENEFITS OF RANGE SAFETY CONTROL

10.5.1 Range Safety Control System Reliability

Range Safety Control systems have played a very important role in the success of the space program. Combined with an outstanding Risk Prevention and Control program, their success has been such that there have been no casualties resulting from in-flight launch vehicle failures. As mentioned in Ch. 4, this is due to both mission planning and to the design standards and performance reliability of the Flight Termination Systems (FTS). The USAF design goal for FTS hardware reliability is .999 at a 95% confidence level for WSMC and ESMC, whereas the WSMR design goal for sub-orbital ELV's is .997 to the same confidence level (see Ch.8 and Ch.9 discussions of reliability vs. safety). Performance testing and verification of the FTS reliability depends on the number of such failures, environmental stress during testing or accident and on other accident specifics. The reliability that has been achieved is due in part to the redundancies built into both the ground and airborne components of the systems. There are no published figures on the operational reliability of Range Safety systems, but with hundreds of vehicles destroyed with no system failures, one could conclude that the probability of system failure is less than 1 in 1000.

10.5.2 Loss and Casualty Potential When Range Safety Controls Are Not Used

The following is intended to discuss worst case loss situations for space launches, assuming that vehicles are launched and fail over communities and that Range Safety Controls (chiefly a Flight Termination System provided on-board the ELV, as described in Ch.2, Vol.1) are not in place. A computer model, Community Damage (COMDAM), was developed for this special purpose. The concept for this model is shown in Figure 10-13.

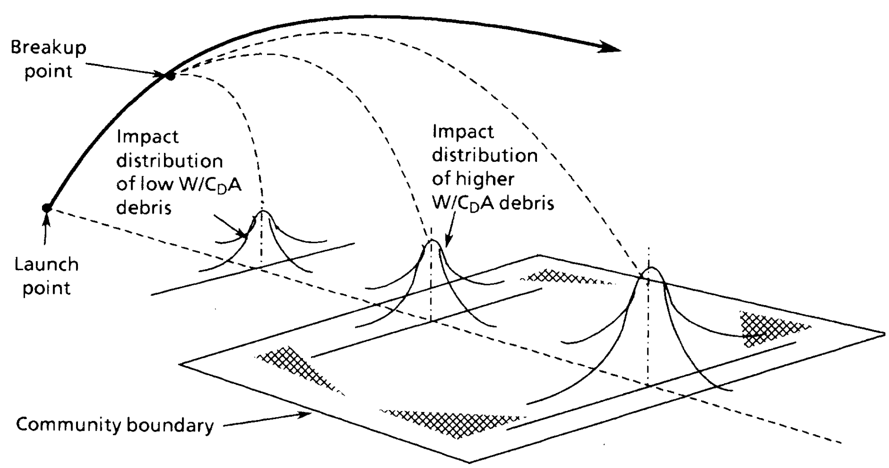


FIGURE 10-13. COMMUNITY DAMAGE MODEL OF DEBRIS LANDING ON A COMMUNITY - COMDAM

The model is deterministic, not probabilistic (see Ch. 8), i.e., given a catastrophic ELV failure and the absence of a destruct system, it examines the nature and severity of possible consequences of interest, namely a conditional casualty expectation. In reality, implementation of Range Safety restricts launch azimuths as well as decreasing the likelihood of any accident that could have public impacts (see Ch.9).

The launch vehicle is assumed to overfly and fail above a community located in the vicinity of the Range. This model might apply to evaluating damage from debris impacting in the vicinity of a Range, say, to Santa Barbara or the Channel Islands near WSMC, or to Miami Beach near ESMC, or to Albuquerque near WSMR. These scenarios are obviously unrealistic because launch vehicles are neither allowed to overfly populated areas nor allowed to proceed without certified Flight Termination Systems. On the other hand, COMDAM may afford insight into the potential of unconstrained launch operations for accidental casualty and property loss.

For simplicity, the hypothetical community at risk is laid out as a square, with several types of structures spaced evenly over the area within the community boundaries. The ELV is assumed to fail and break into pieces spontaneously due to aerodynamic stress. These fragments must be classified according to their ballistic coefficient and explosiveness (if solid propellant). The debris can be dispersed by scattering (lift/drag) effects and velocity impulses which may be imparted to the debris at the time of an explosive in-flight failure. If a piece of debris impacts the ground and explodes, the overpressure (P) and impulse (I) are computed on all of the adjoining structures (see also Ch.5, Vol.2). The explosive damage to each structure is computed using the formula $D = a(P^b)(I^c)$, where D is the percent damage and the coefficients a, b and c are unique for each different structure class and were developed from data gathered from explosive accidents.[9,10] If the structure is calculated to be more than sixty percent damaged, it is assumed that it must be totally replaced and, thus, equivalent to being 100% damaged. The dollar loss is obtained by multiplying percent damage times the average building value.

For damage due to inert (non-explosive) debris, kinetic energy thresholds are set. If the kinetic energy of an impact fragment did not exceed a pre-specified level, it is assumed not to penetrate the structure and cause any damage. If it did exceed the threshold, the damage to the structure is assumed to be the ratio of the area of the fragment to the projected area of the structure. Casualty expectations, E_C, were computed using the model developed in Ref. 13.

The flow diagram for this specifically adopted analytical procedure is shown in Figure 10-14. These algorithms and logic can be programmed and used to estimate the approximate expected losses and casualties similar to those discussed above. One of the reasons for developing such an unrealistic worst-case consequence model was to show several effects, such as:

1) the change in total losses as a function of the time of launch vehicle failure:

2) the effect of the distance from the point of launch on the population center at risk; and

3) the influence of exploding debris.

The COMDAM numbers must be treated as approximate at best, and illustrative only, since no specific community has been considered and the consequences of accidents can vary significantly even under essentially the same conditions. The financial (dollar loss) consequence estimates consider only damage, and not business interruption costs.

It should be noted that the above model accounts for structural damage produced by:

1- direct impact of inert fragments

2- blasts triggered by the explosion of burning fragments upon impact with ground.

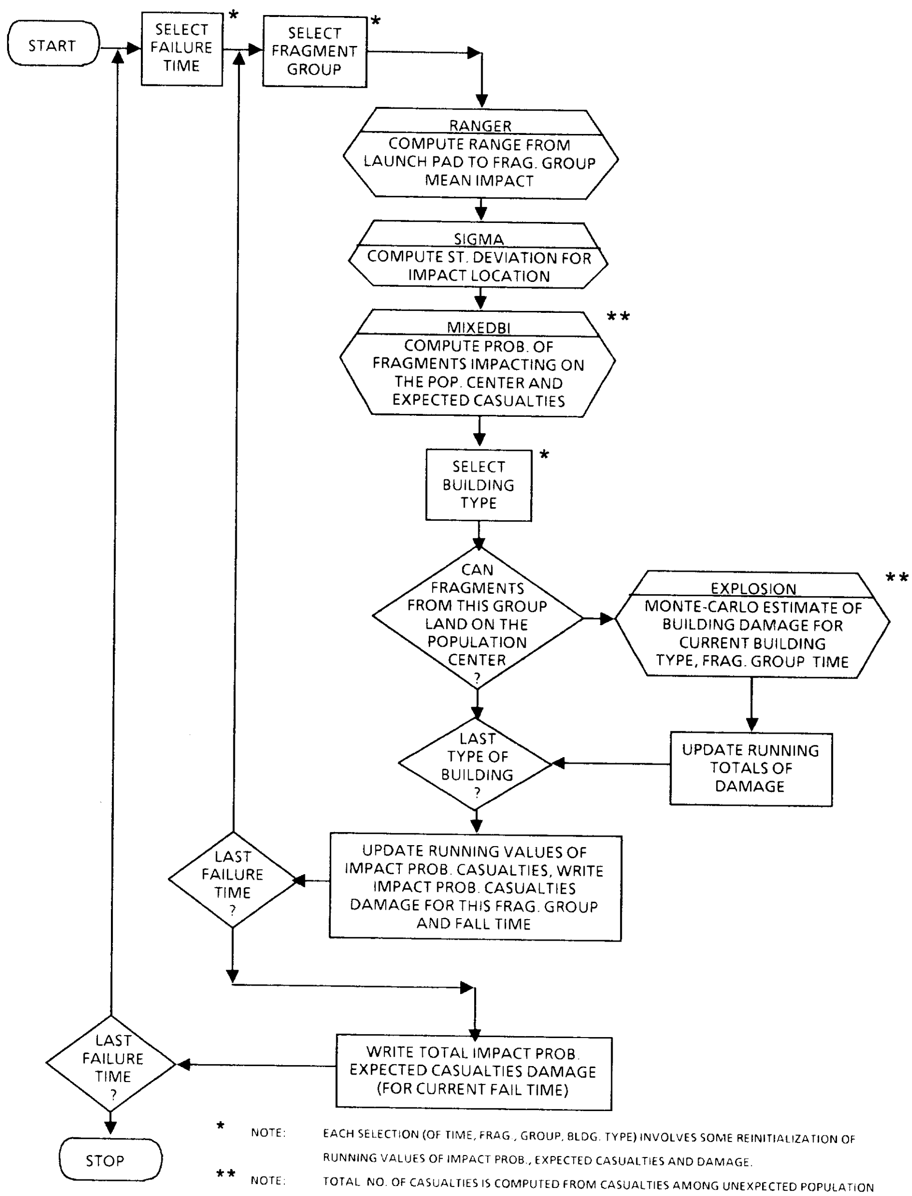
Damage mechanisms not included in the model are:

a- fires initiated by burning fragments upon impact with ground (e.g., brush fires, gas main explosions and fires).

b- vapor clouds produced by burnt/unburned propellants.

c- blast and fire ball produced in the air at the instant of vehicle breakup.

This COMDAM model does not predict what would occur realistically, but rather what is the worst that could happen. With the addition of launch azimuth restrictions enforced to avoid land overflight, the provision of a highly reliable FTS on-board the ELV and an effective ground-based Range Safety Control network, such public damage and casualties as a consequence of launch accidents become highly unlikely.



* NOTE: EACH SELECTION (OF TIME, FRAG., GROUP, BLDG. TYPE) INVOLVES SOME REINITIALIZATION OF RUNNING VALUES OF IMPACT PROB., EXPECTED CASUALTIES AND DAMAGE.

** NOTE: TOTAL NO. OF CASUALTIES IS COMPUTED FROM CASUALTIES AMONG UNEXPECTED POPULATION (COMPUTED BY SUBROUTINE MIXEDBI) SUMMED WITH CASUALTIES TO PERSONS IN BLDG'S (BASED ON THE PERCENT OF BUILDING DESTROYED)

FIGURE 10-14. GENERAL FLOW DIAGRAM OF COMMUNITY DAMAGE MODEL, COMDAM

10.5.3 Comparison of Risk Acceptability

MIL-STD-882B provides only qualitative definitions of the severity and frequency of accidents for the purpose of risk assessment.(12) These definitions are reproduced in Tables 10-1 and 10-2, since they could be used to demonstrate the relative acceptability of risks from launch vehicles both with and without Range Safety Controls in place.

Although these qualitative definitions apply to military systems including space system certification, acceptance and failure risk analysis, they can also be applied to hazard assessment for commercial launches.

Tables 10-3 and 10-4 give two examples from MIL-STD-882B for risk acceptability, in the form of a hazard risk assessment matrix.(12)

The next step is to find the risk associated with ELV launches in the hazard frequency/acceptability format exhibited in the previous four tables. When a vehicle (e.g., Titan, Atlas/Centaur or Delta) is not under Range Safety Control, there is potential for catastrophe if the vehicle fails fairly early in flight near or over a community. Since all prospective commercial launch vehicles have a historical launch failure frequency of more than 4 percent (range from 4 to 14 percent) (see Ch. 3, Vol 1), this must be considered an "occasional event." With the Range Safety Control System in place, there is potential for catastrophe only when this system fails to perform its function. Given the proven reliability of modern Range Safety Control systems, the occurrence of a accidental failure with major public safety impacts must be considered improbable or remote.

As the vehicle progresses from launch toward achieving orbit, the associated risk to the public is reduced, as discussed in Section 10.2.3. At this stage the Range Safety System provides little or no benefit, because the debris produced from high altitude destruct action will be similar to that without destruct and there is no way to restrict the impact location of the debris. Consequently, both with and without a Range Safety Control System, the risk to the public is approximately the same in the pre-orbital and orbital stage, a marginal hazard with a remote probability of occurrence. In returning from orbit (uncontrolled re-entry), there is no possibility of Range Safety Control and the public risk is again marginal, with a remote probability of debris causing any casualties.

TABLE 10-1. HAZARD SEVERITY DEFINITIONS (MIL-STD-882B)

Description	Category	Mishap Definition
Catastrophic	I	Death or system loss.
Critical	II	Severe injury, severe occupational illness or major system damage.
Marginal	III	Minor injury, minor occupational illness or minor system damage.
Negligible	IV	Less than minor injury, occupational illness or system damage.

TABLE 10-2. HAZARD PROBABILITY DEFINITIONS (MIL-STD-882B)

Description (1)	Level	Specific individual item	Fleet or inventory (2)
Frequent	A	Likely to occur frequently.	Continually experienced.
Probable	B	Will occur several times in life of an item.	Will occur frequently.
Occasional	C	Likely to occur sometime in life of an item.	Will occur several times.
Remote	D	Unlikely, but possible to occur in life of an item.	Unlikely, but can reasonably be expected to occur.
Improbable	E	So unlikely it can be assumed occurrence may not be experienced.	Unlikely to occur, but possible

TABLE 10-3. FIRST EXAMPLE, HAZARD/RISK ASSESSMENT MATRIX (MIL-STD-882B)

Frequency of occurrence	Hazard Categories			
	I Catastrophic	II Critical	III Marginal	IV Negligible
(A) Frequent	1A	2A	3A	4A
(B) Probable	1B	2B	3B	4B
(C) Occasional	1C	2C	3C	4C
(D) Remote	1D	2D	3D	4D
(E) Improbable	1E	2E	3E	4E

Hazard Risk Index	Suggested Criteria
1A, 1B, 1C, 2A, 2B, 3A	Unacceptable.
1D, 2C, 2D, 3B, 3C	Undesirable (Management Authority Decision Required).
1E, 2E, 3D, 3E, 4A, 4B	Acceptable with review by management authority.
4C, 4D, 4E	Acceptable without review.

TABLE 10-4. SECOND EXAMPLE, HAZARD/RISK ASSESSMENT MATRIX (MIL-STD-882B)

Frequency of occurrence	Hazard Categories			
	I Catastrophic	II Critical	III Marginal	IV Negligible
(A) Frequent	1	3	7	13
(B) Probable	2	5	9	16
(C) Occasional	4	6	11	18
(D) Remote	8	10	14	19
(E) Improbable	12	15	17	20

Hazard Risk Index	Suggested Criteria
1 - 5	Unacceptable.
6 - 9	Undesirable (Management Authority Decision Required).
10 - 17	Acceptable with review by management authority.
18 - 20	Acceptable without review.

These conclusions about the relative public risks associated with ELV launches are summarized in Table 10-5 using the definitions of hazard, frequency and acceptability as specified in MIL-STD-882B.[12]

The conclusion is that a Range Safety Control Systems must be in place so that normal, though relatively low probability, launch failures become tolerable and permissible from the point-of-view of public safety.

Figure 10-15, reproduced from Ref 14, is a Public Launch Hazard Event Tree based on ESMC launch experience, but it also applies conceptually to the other National Ranges. It shows that a long chain of failure events must take place to expose the public to launch or overflight hazards. Conditional probabilities and branching of events are also indicated. This type of analysis will be applied to evaluate the safety risks associated with specific ELV's, launch sites and missions.

TABLE 10-5. RELATIVE RISKS FOR VARIOUS FLIGHT PHASES WITH AND WITHOUT RANGE SAFETY SYSTEMS

Flight Phase	Without Range Safety Control			With Range Safety Control		
	Hazard level	Frequency	Acceptability	Hazard Level	Frequency	Acceptability
Early Launch	Potentially catastrophic	Occasional	Unacceptable	Potentially catastrophic	Improbable	Acceptable
Pre-orbital	Marginal	Remote	Acceptable	No benefit	No benefit	No benefit
Return from orbit (uncon-trolled)	Marginal	Remote	Acceptable	No Possible control	No Possible control	No Possible control

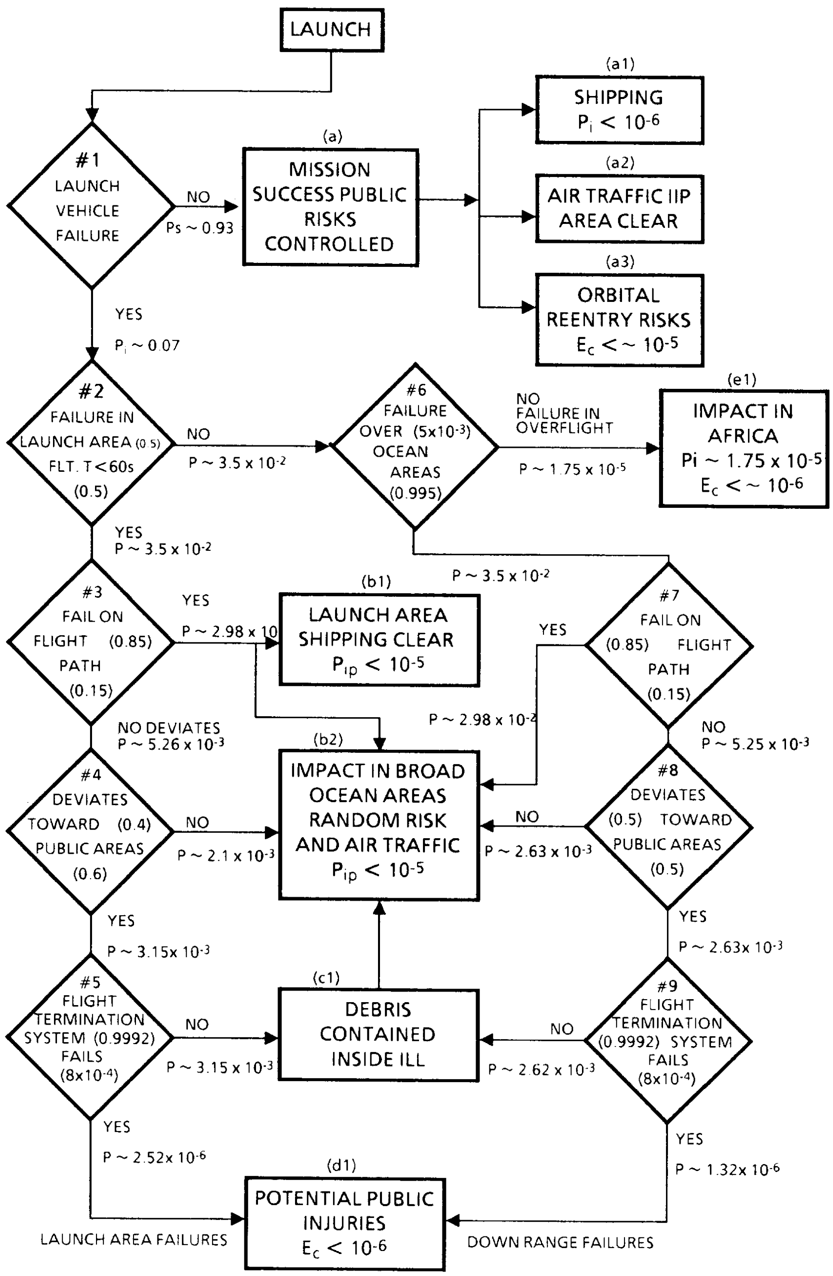


FIGURE 10-15 PUBLIC LAUNCH HAZARD EVENT TREE

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